AGU 2025 - H52B-01
New Orleans
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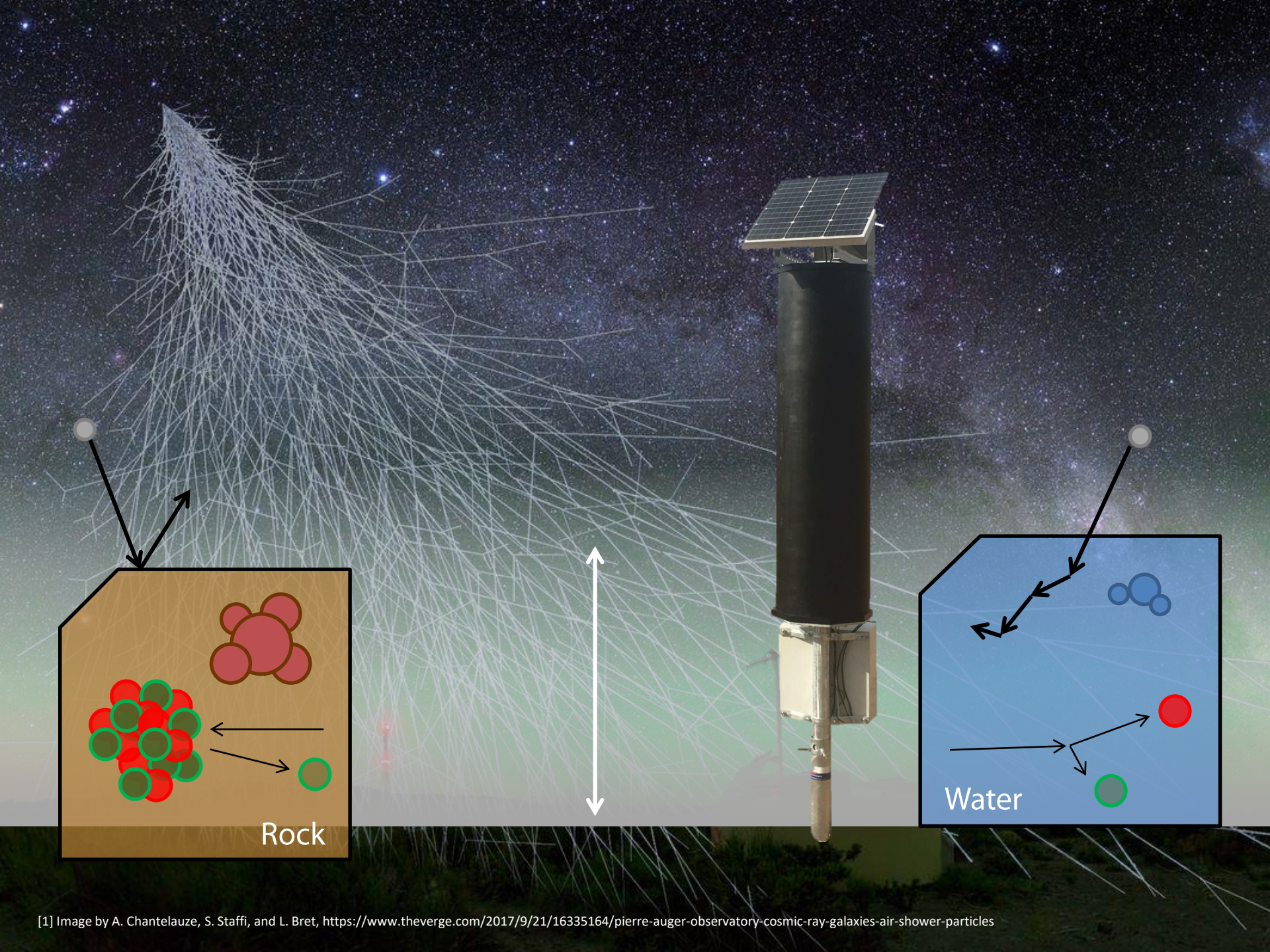
Soil moisture measurements based on Cosmic-Ray Neutron Sensing – current status and open questions

Markus Köhli[1,2]

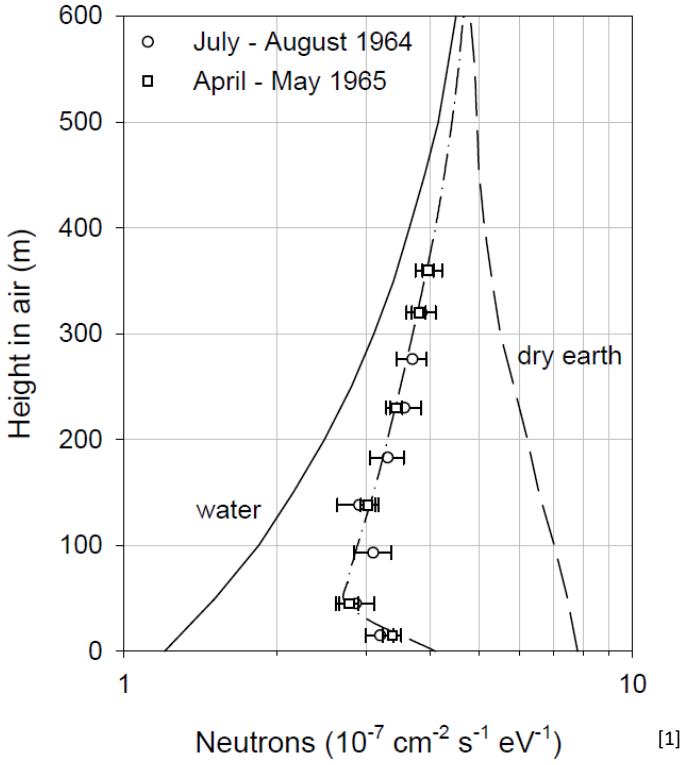
[1] Physikalisches Institut, Heidelberg University, Germany
[2] StyX Neutronica GmbH, Mannheim, Germany

Physikalisches Institut
Heidelberg University
Germany



[1] Image by A. Chantelauze, S. Staffi, and L. Bret, https://www.theverge.com/2017/9/21/16335164/pierre-auger-observatory-cosmic-ray-galaxies-air-shower-particles

Historical Overview

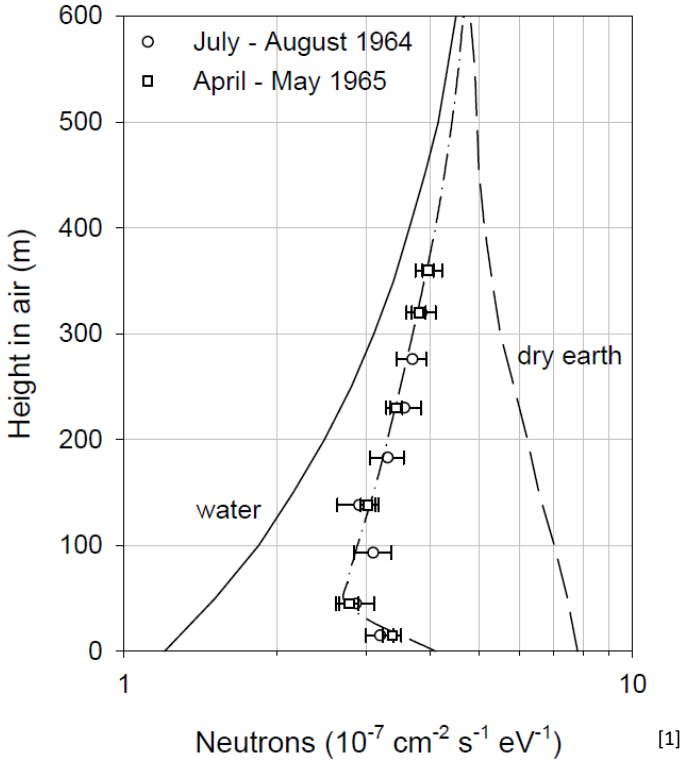


[1]

1966

[1] Hendrick, L. D. and Edge, R. D., “Cosmic-ray neutrons near the Earth”, Phys. Rev. Ser. II, 145 (1966)
[2] Kodama, M. et al., “Application of atmospheric neutrons to soil moisture measurement”, Soil Sci., 140 (1985)

Historical Overview



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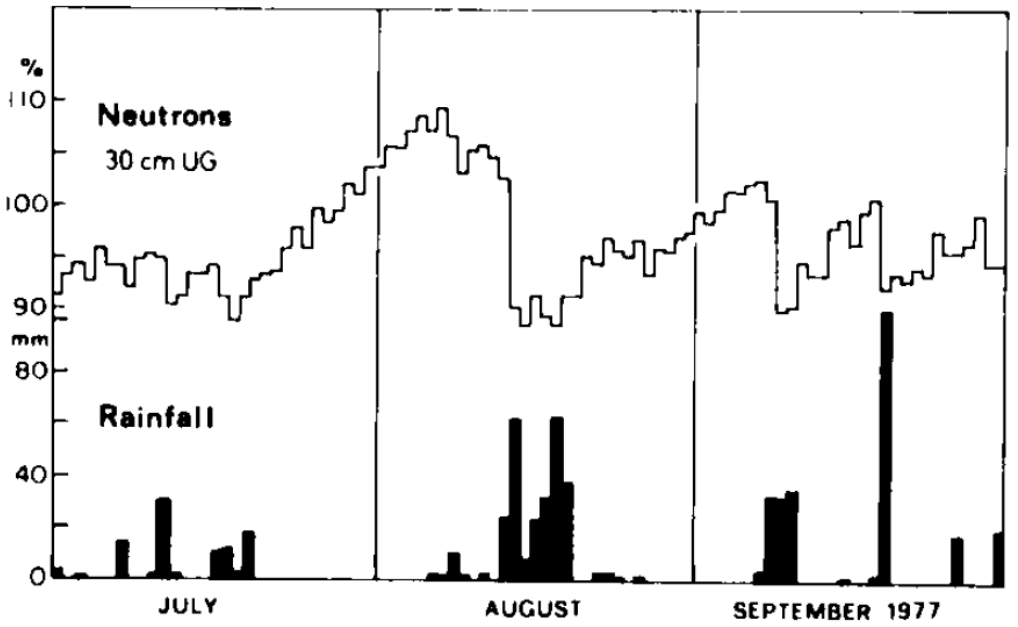

[2]

1966 — 1985

[1] Hendrick, L. D. and Edge, R. D., "Cosmic-ray neutrons near the Earth", Phys. Rev. Ser. II, 145 (1966)
[2] Kodama, M. et al., "Application of atmospheric neutrons to soil moisture measurement", Soil Sci., 140 (1985)

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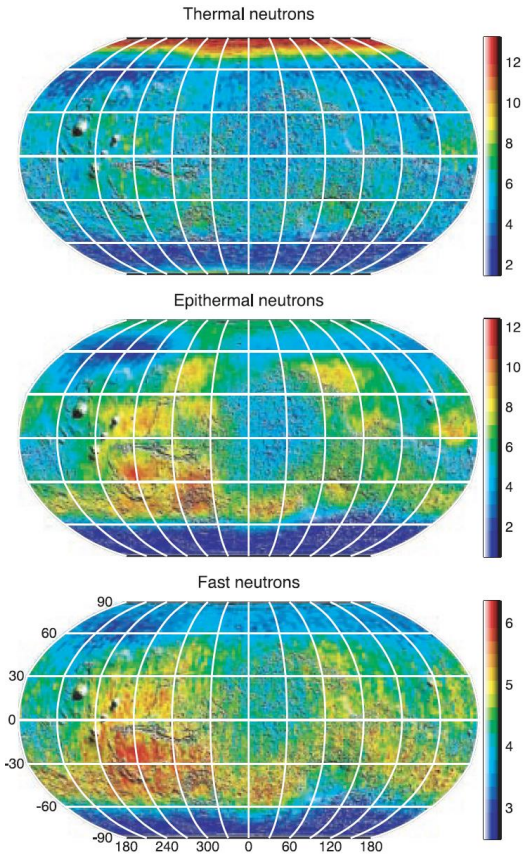
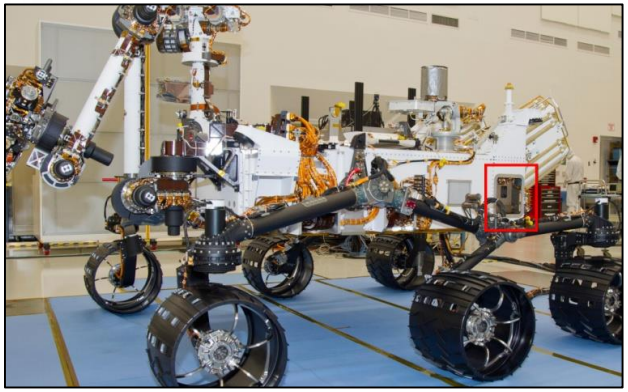


[1]

Curiosity Rover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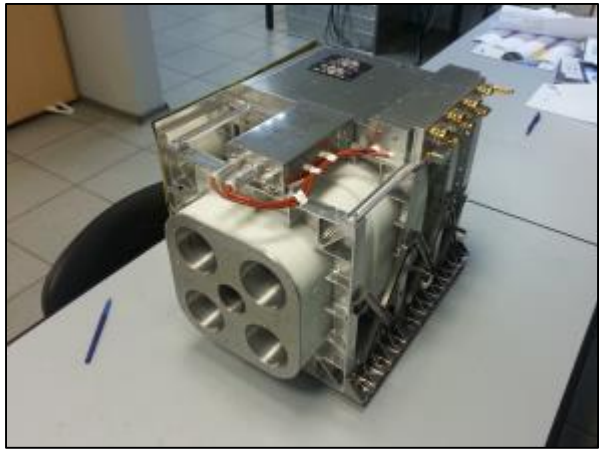
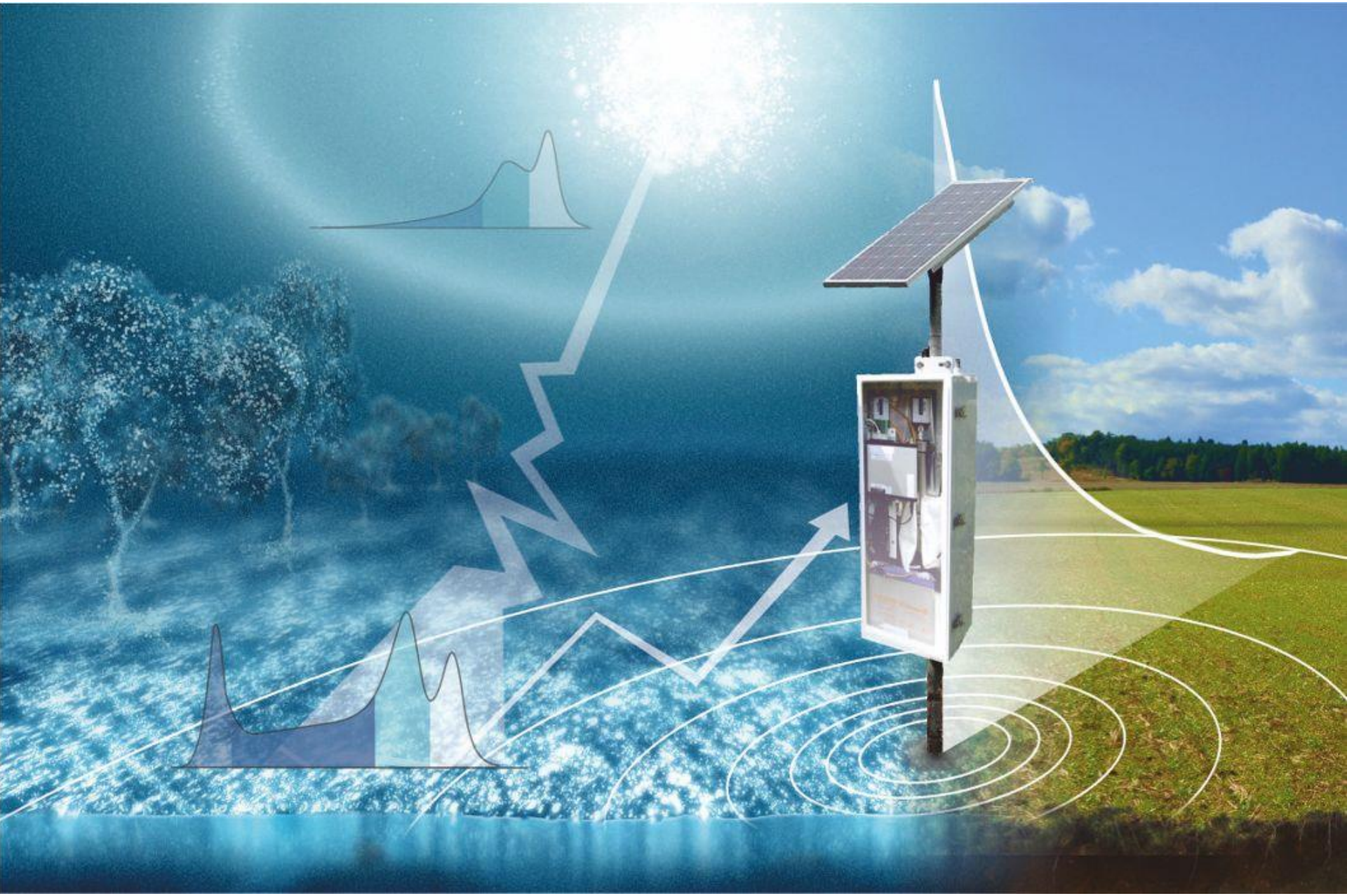


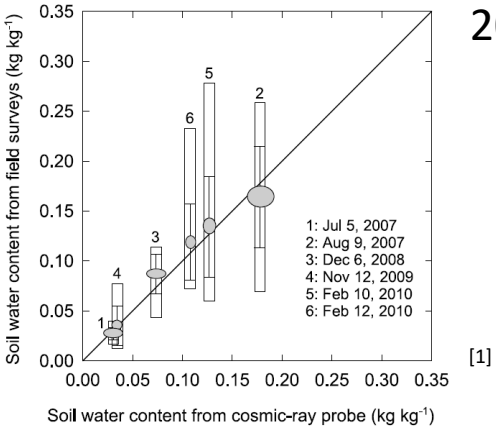
Trace Gas Orbiter

1966 | 1985 | 2000

[1] W.C. Feldman, et. al „Global Distribution of Neutrons from Mars: Results from Mars Odyssey“, Science 297 (5578) (2002), 75-78.
[2] http://exploration.esa.int/mars/48523-trace-gas-orbiter-instruments/?fbodylongid=2217

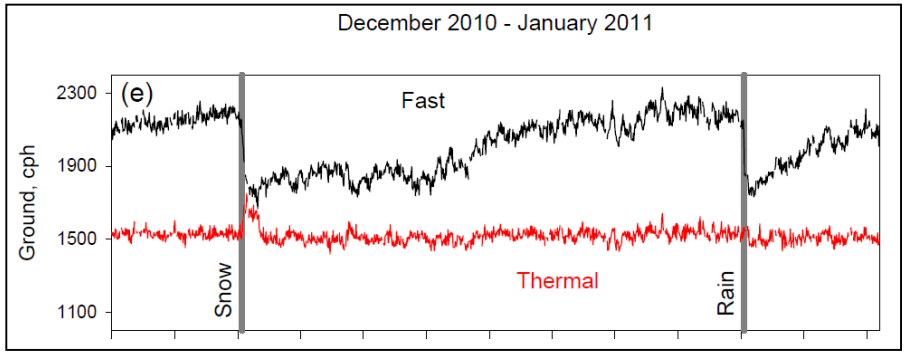


Historical Overview



2010

[1]



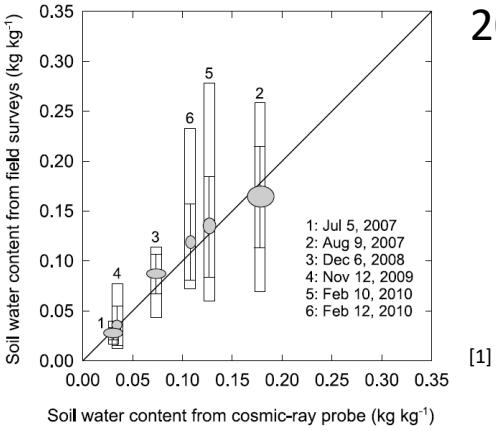
[1]

1966 | 1985 | 2000 | 2010

[1] Zreda, M. et al., "COSMOS: The COsmic-ray Soil Moisture Observing System." Hydrology and Earth System Sciences 16(11) (2012)
[2] Desilets, D. et al.,"Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays.", Water Resources Research 46(11) (2010)

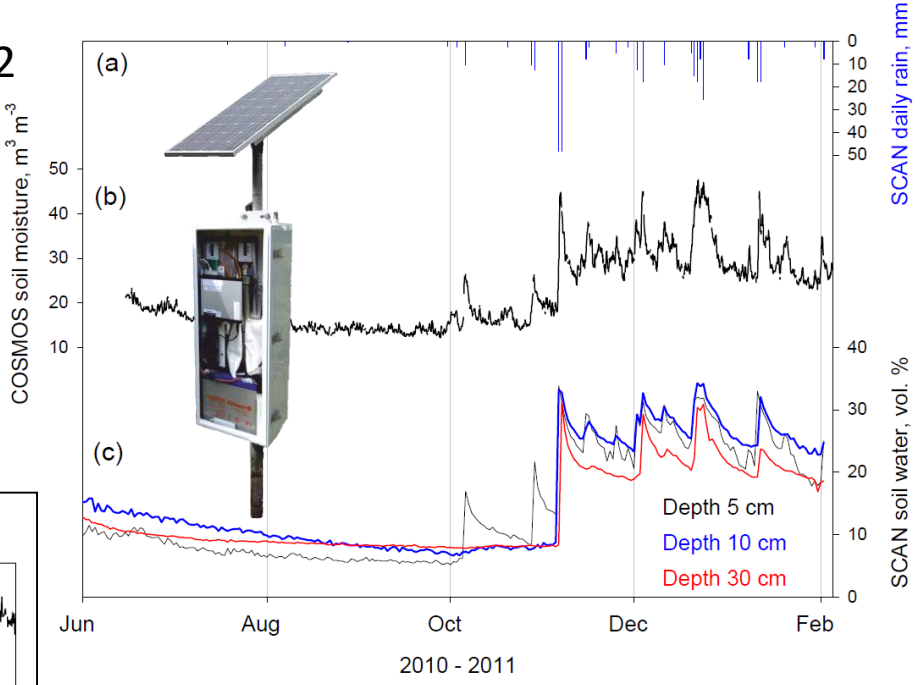
Historical Overview

2010

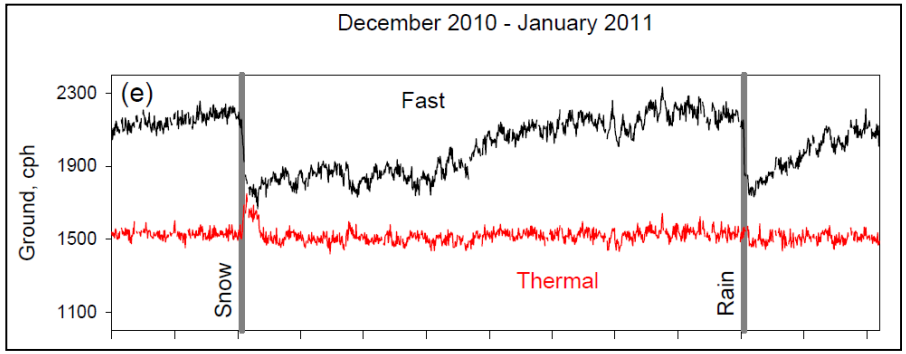


[1]

2012



[2]



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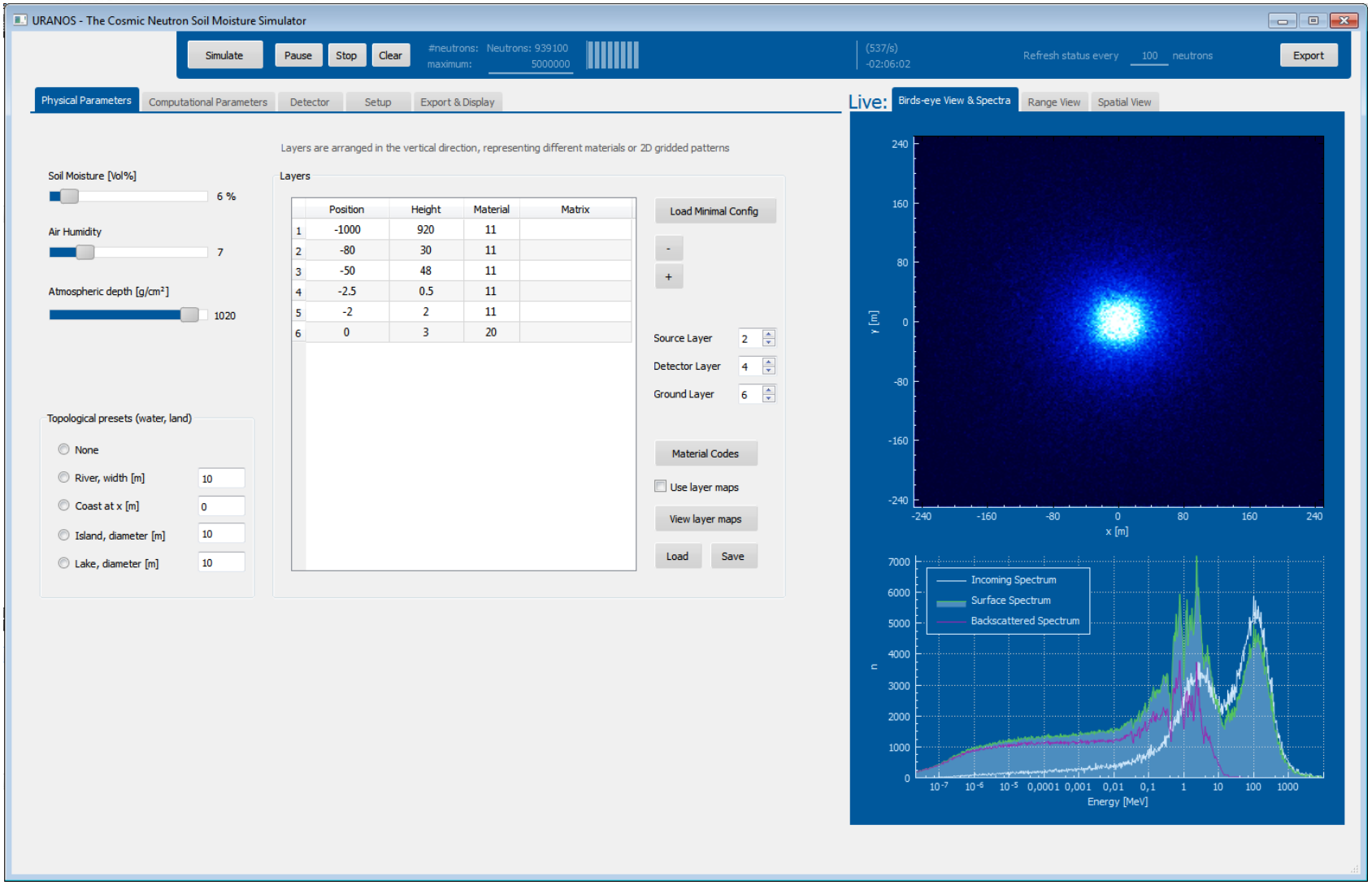
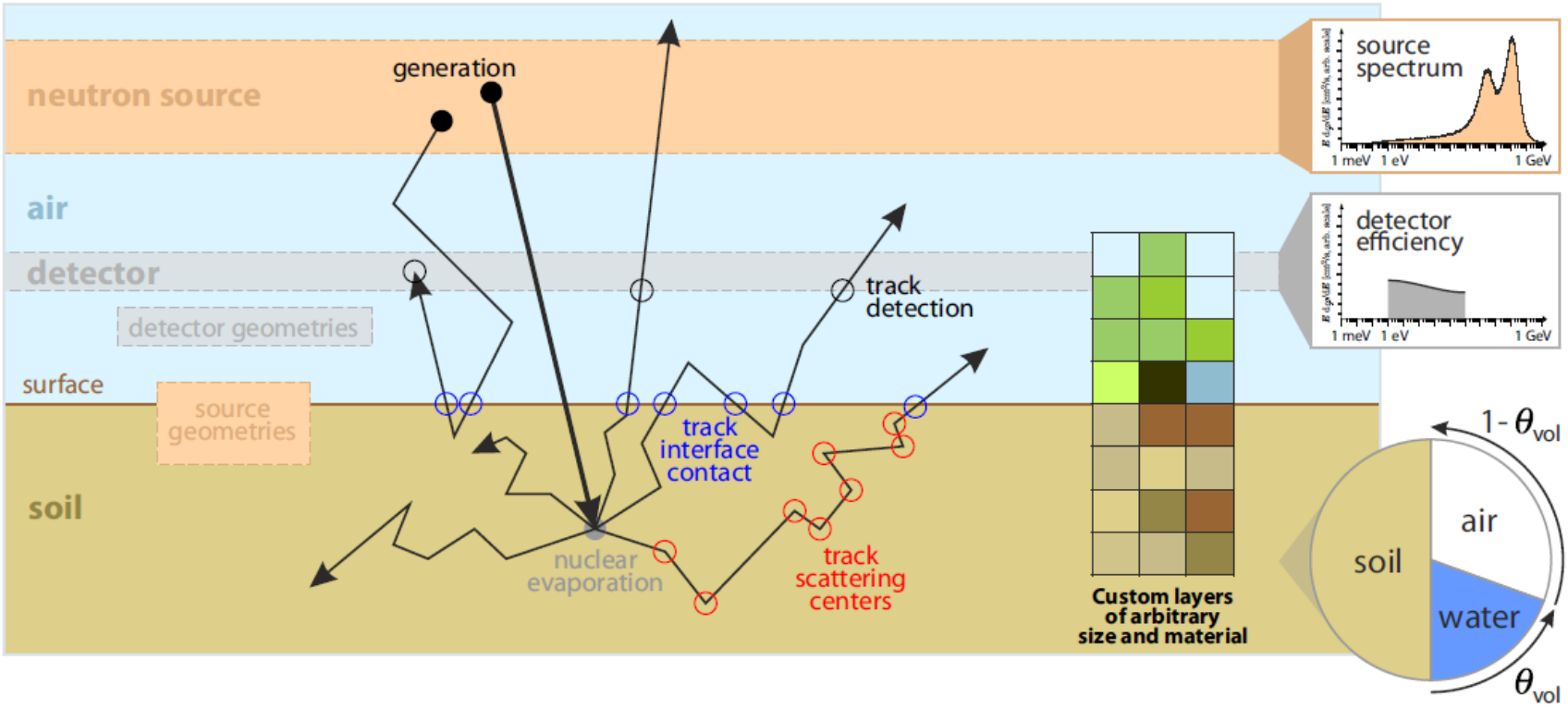
In collaboration with Martin Schrön, UFZ Leipzig

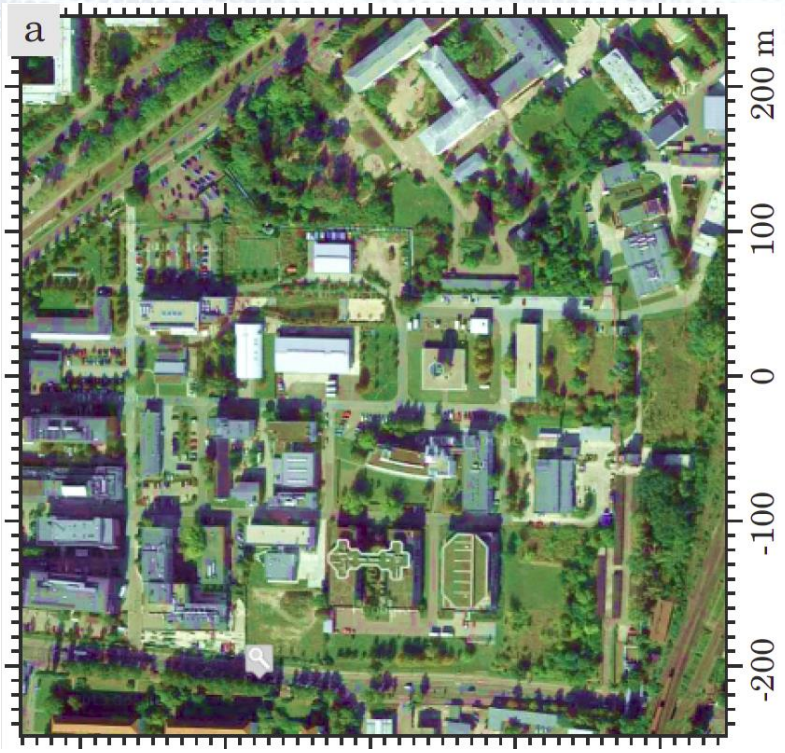


URANOS Buildup

In collaboration with Martin Schrön, UFZ Leipzig

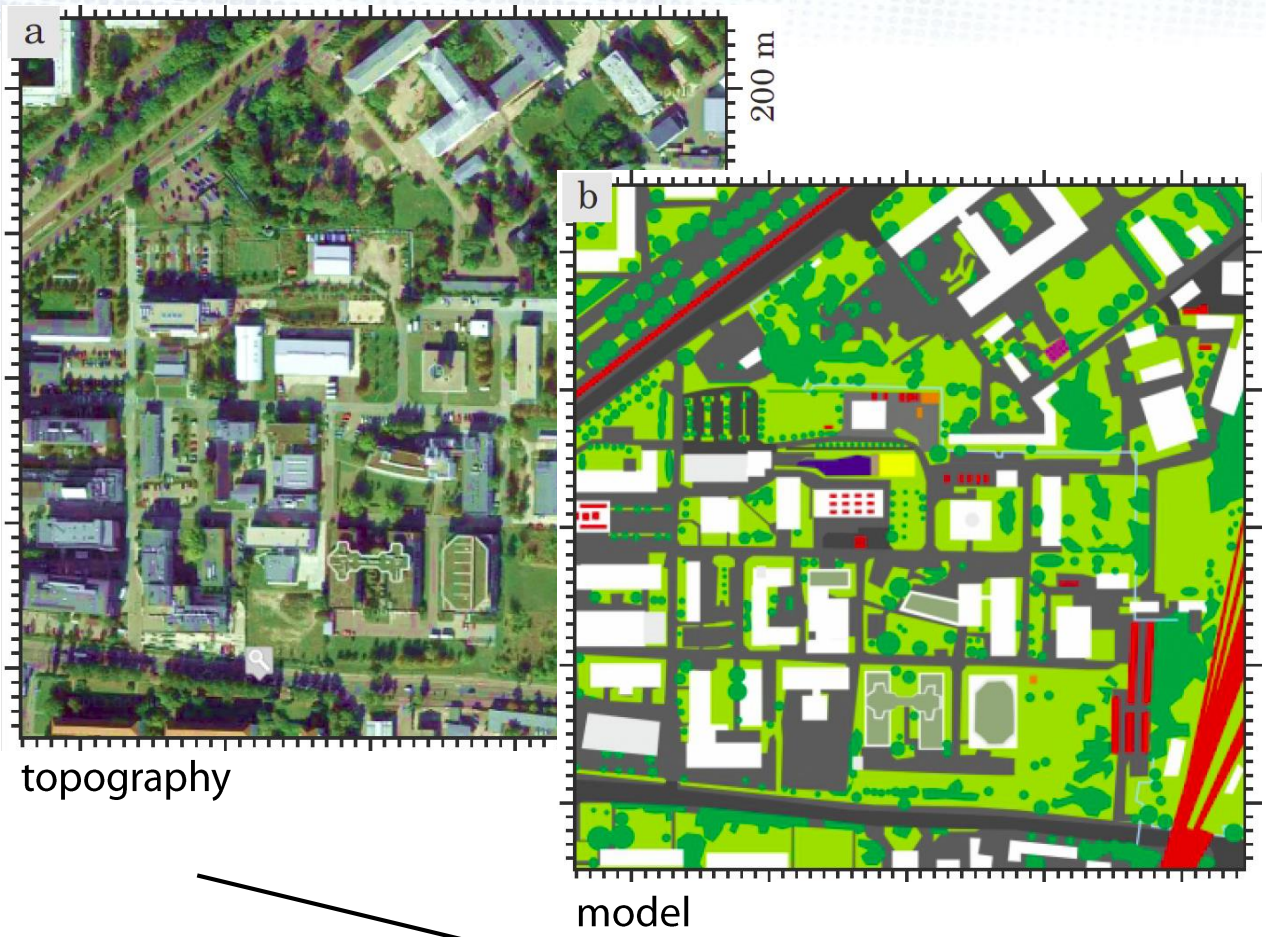


URANOS Modeling



topography

URANOS Modeling



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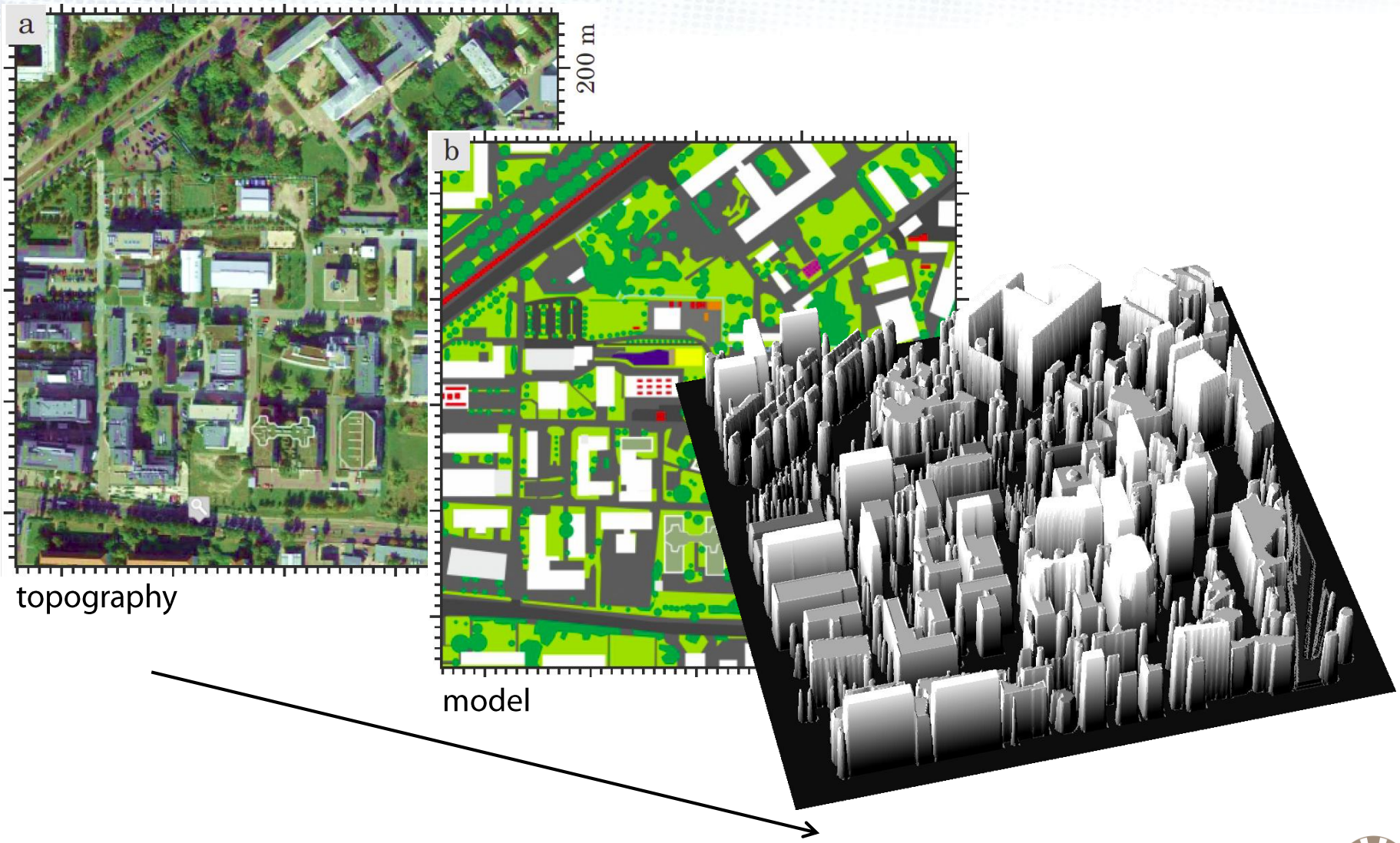

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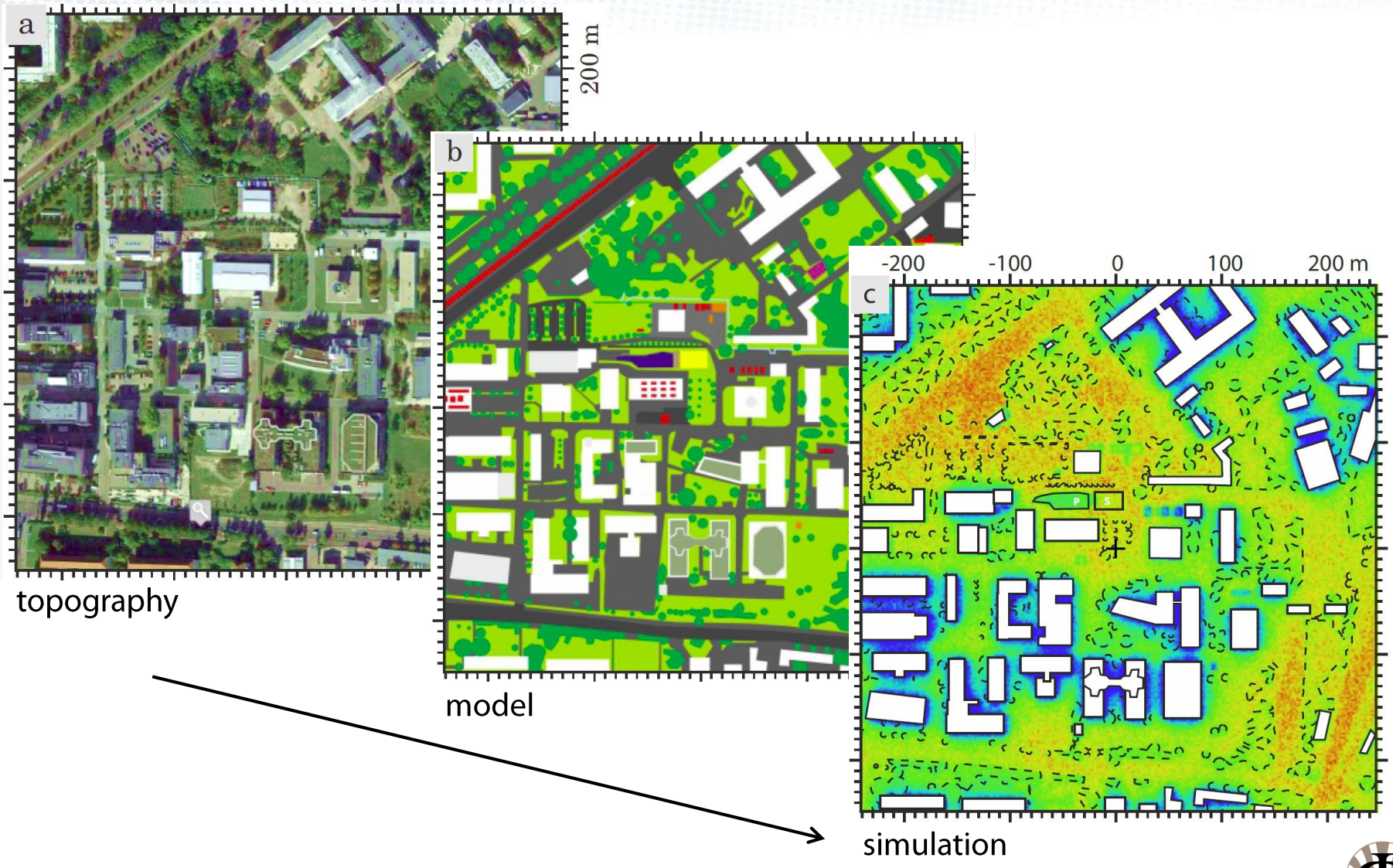
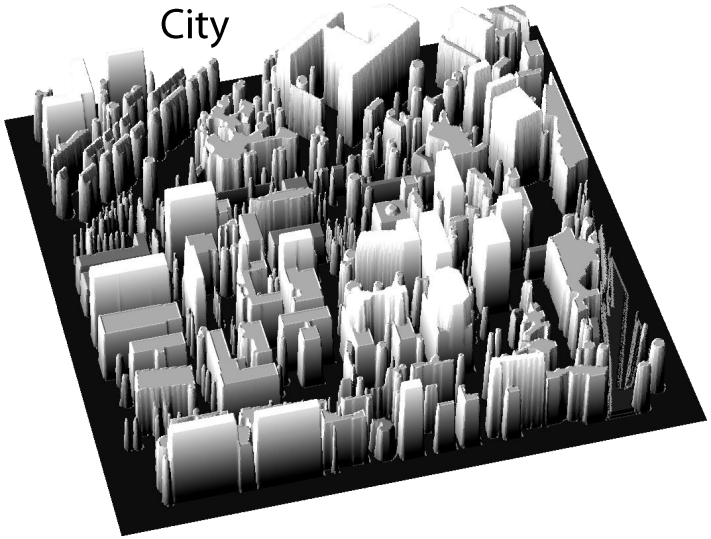
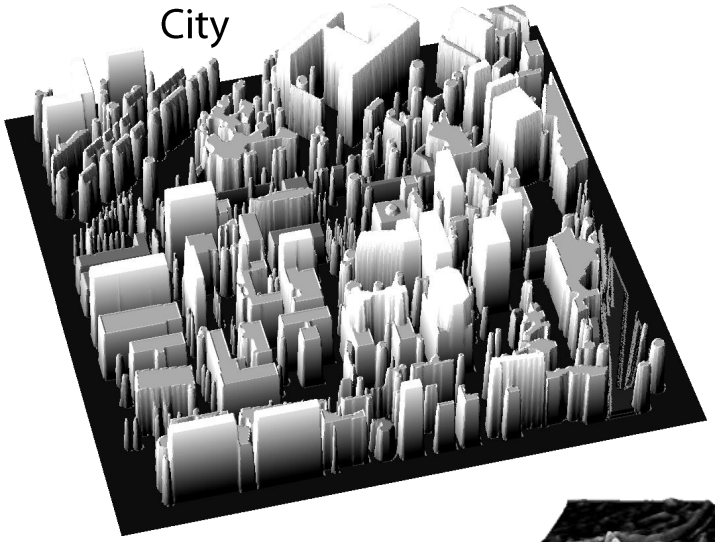


URANOS Modeling

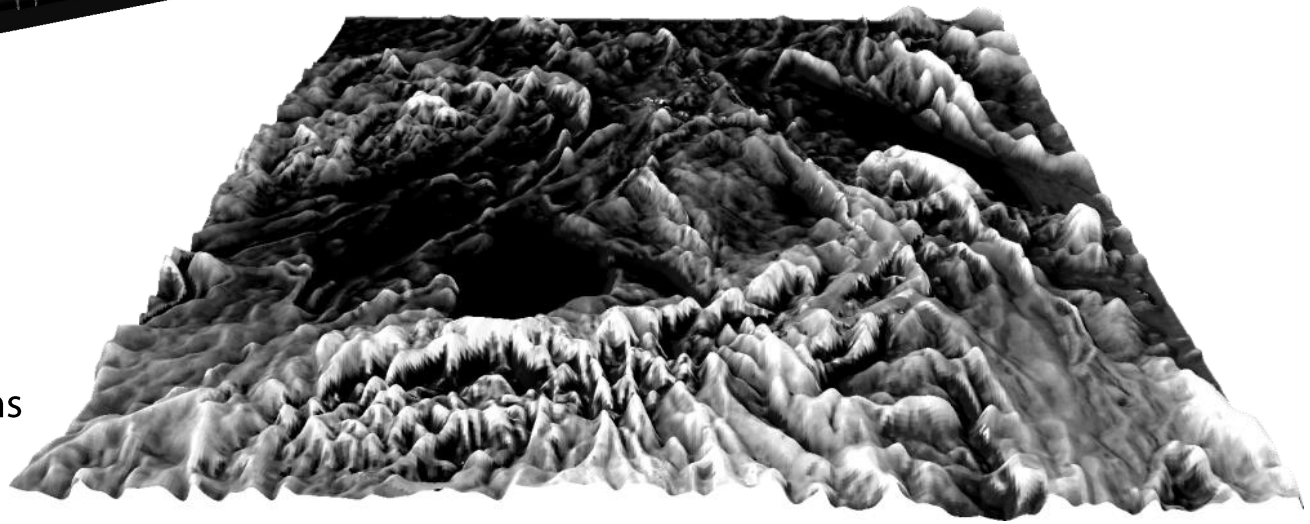


URANOS Modeling

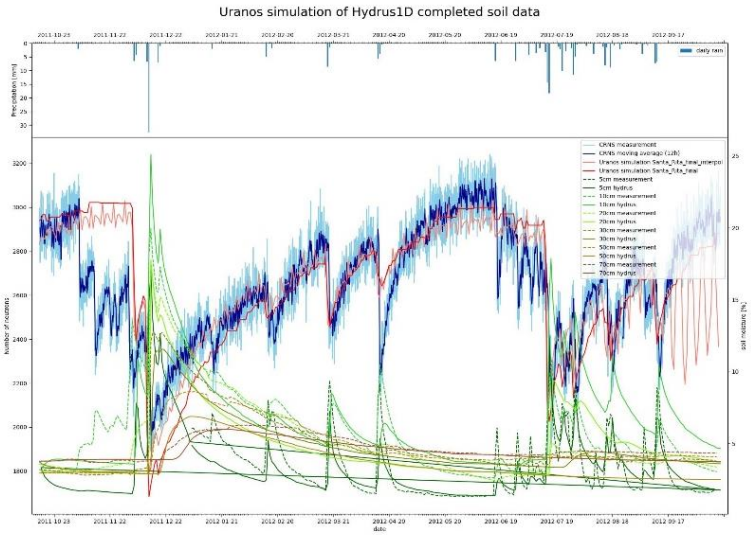
City



Mountains



CRNS timeseries Santa Rita



[1] Rosolem, R. et al. “The Effect of Atmospheric Water Vapor on Neutron Count in the Cosmic-Ray Soil Moisture Observing System.” J. of Hydrometeorology 14(5) (2013)

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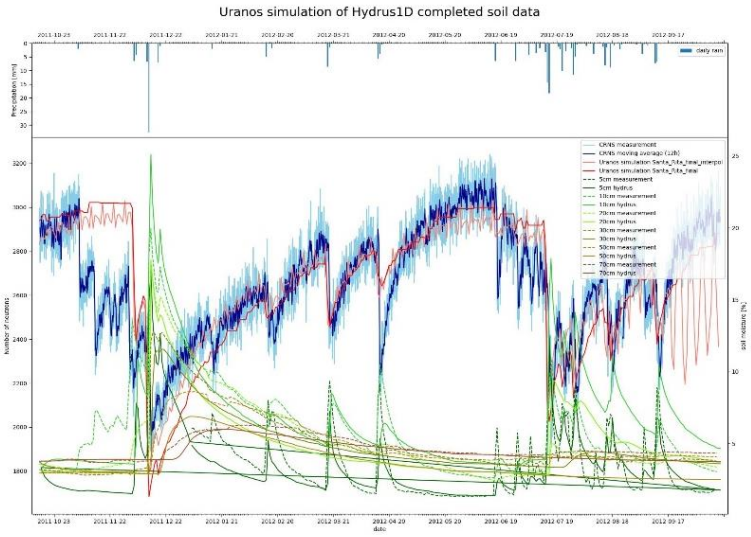

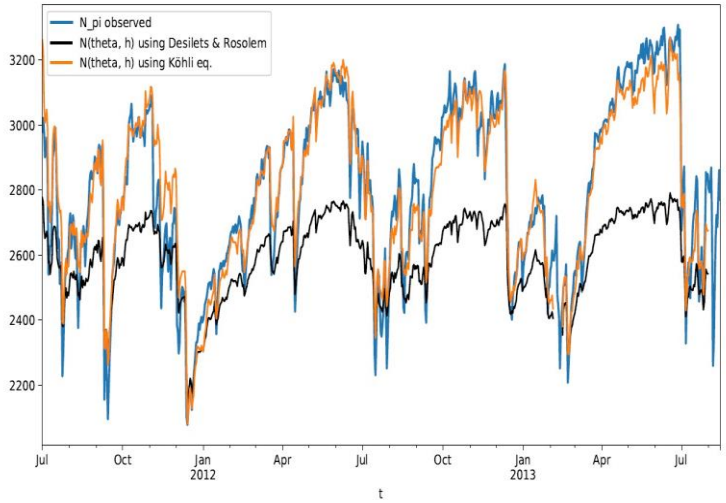

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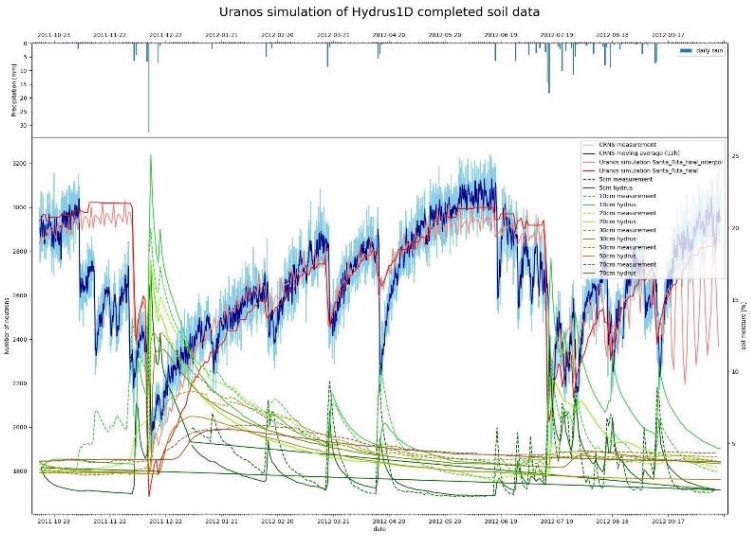

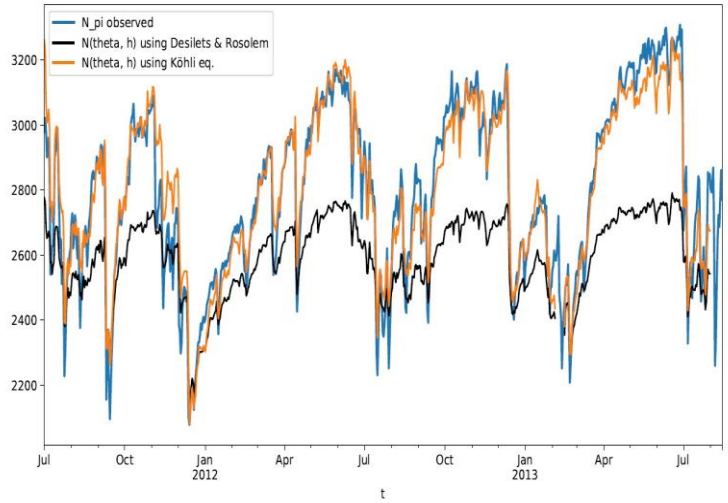

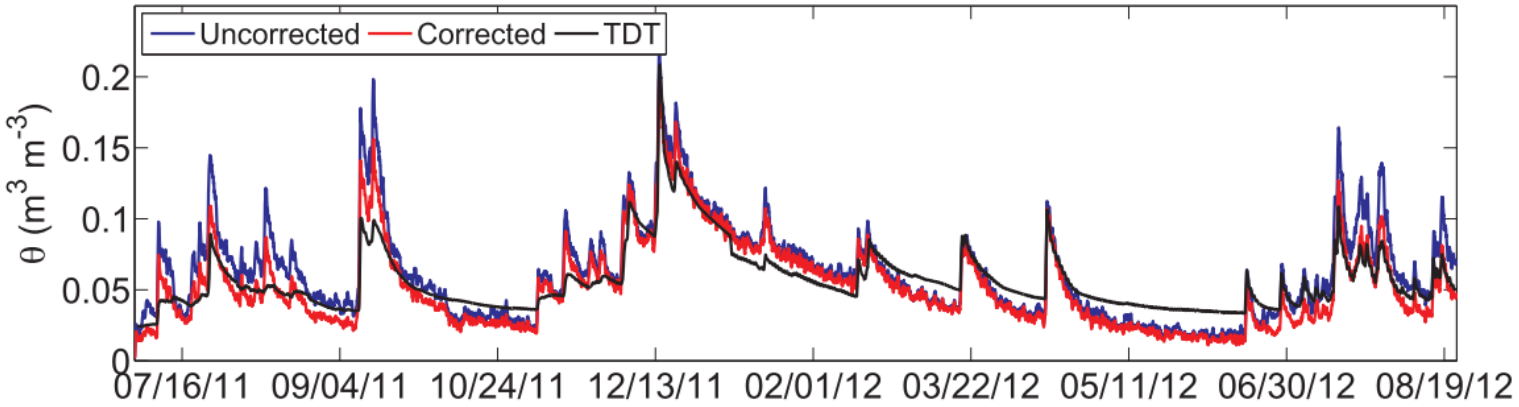

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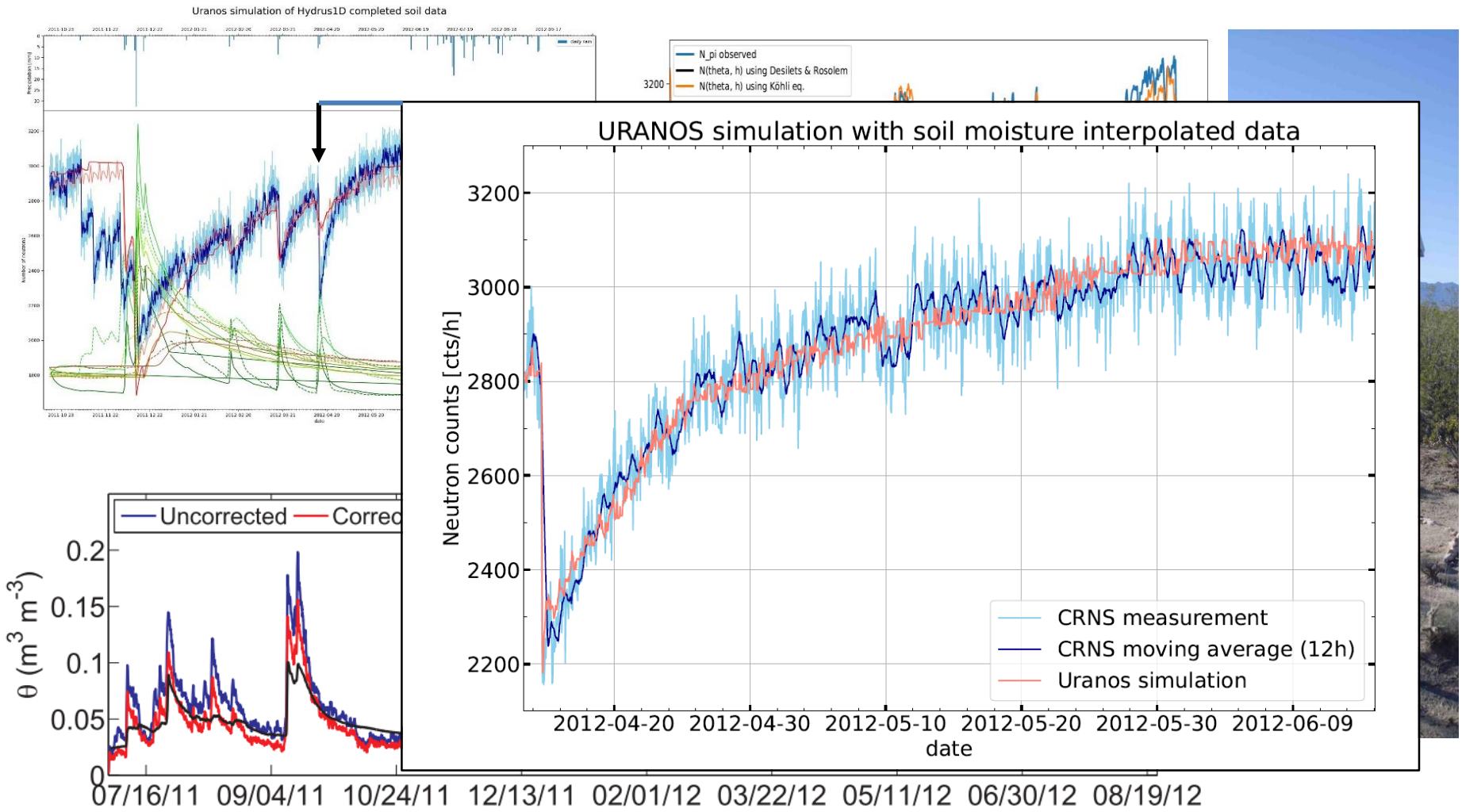

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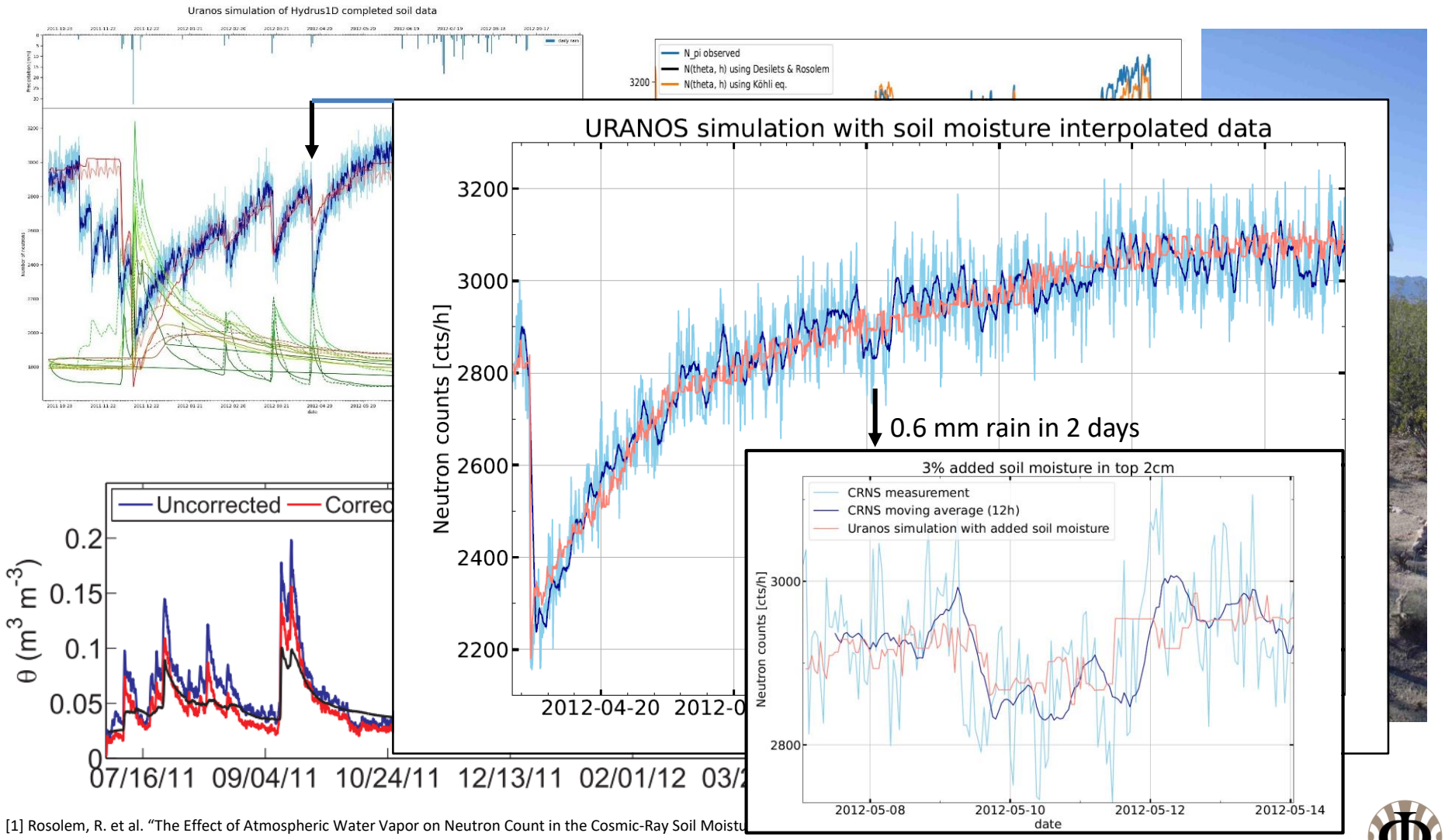

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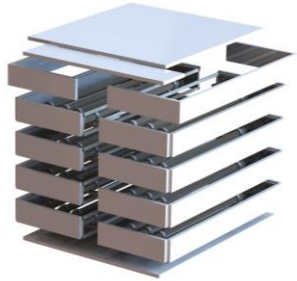
Stationary and Roving

In collaboration with Martin Schrön, UFZ Leipzig



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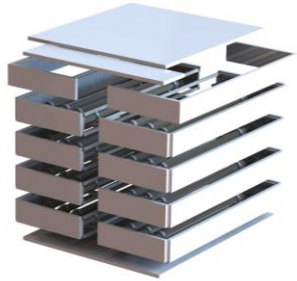


Stationary Instruments

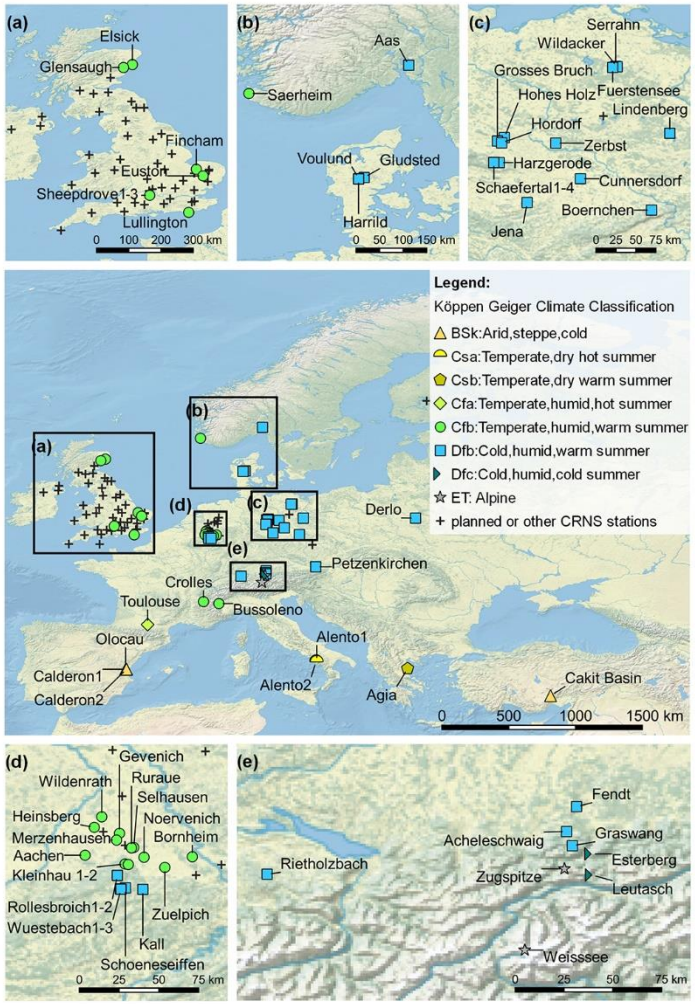
StyX Neutronica SP

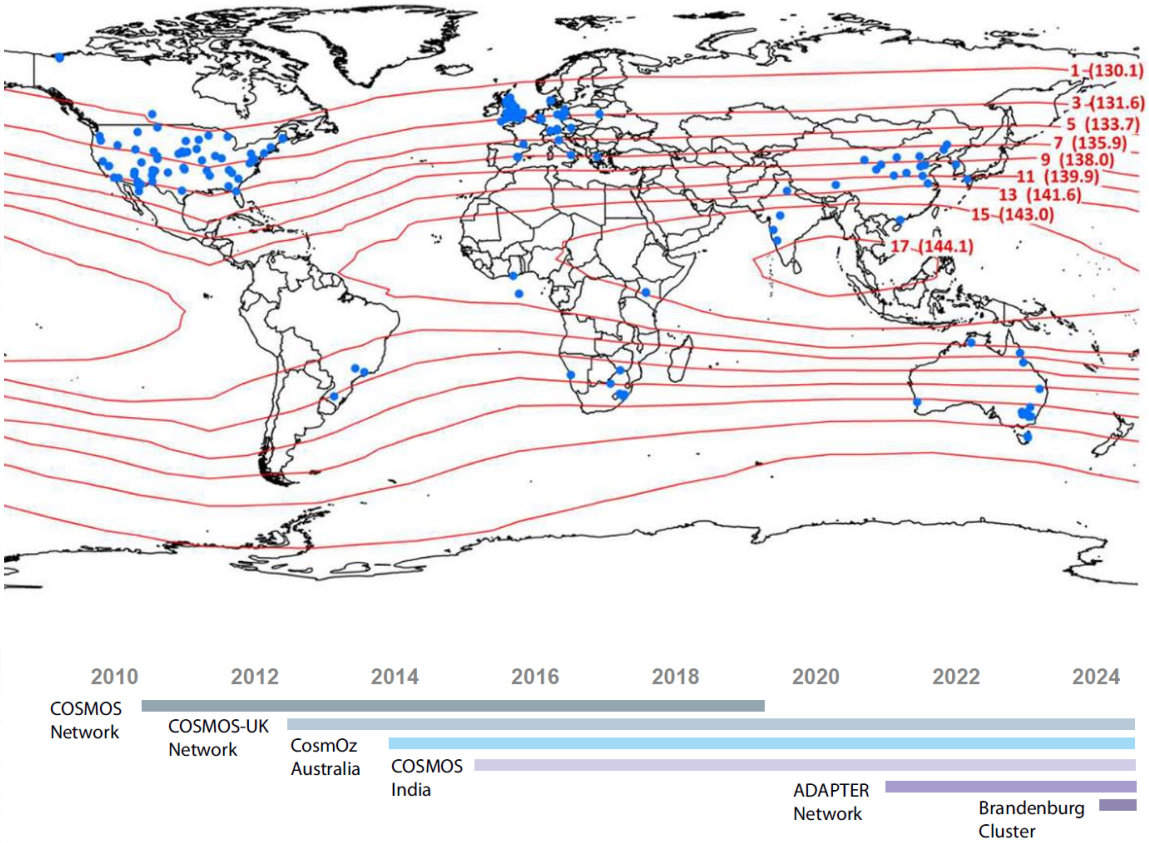
Hydroinnova CRS1000

Finapp 3

StyX Neutronica S1

Stationary Instruments

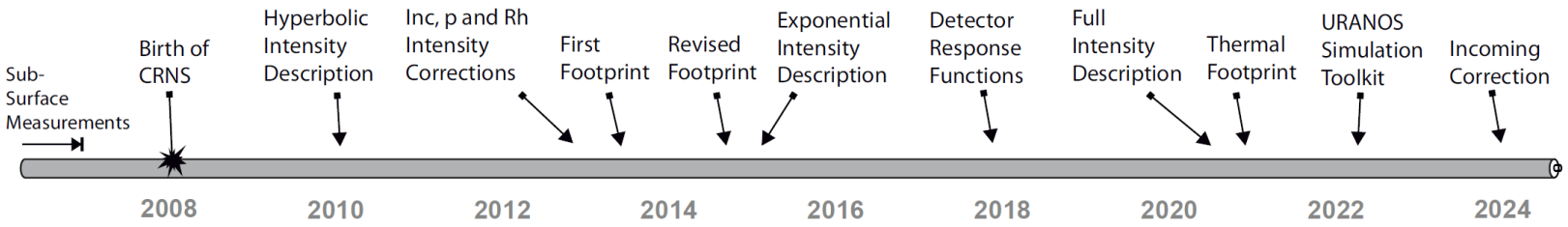




M. Andreasen, et al. "Status and perspectives on the cosmic-ray neutron method for soil moisture estimation and other environmental science applications," Vadose Zone Journal 16 (8) (2017) 1–11,

H. R. Bogena, et al., "Cosmos-Europe: a European network of cosmic-ray neutron soil moisture sensors," Earth System Science Data 14 (3) (2022) 1125–1151, doi:10.5194/essd-14-1125-2022.

Current Open Questions



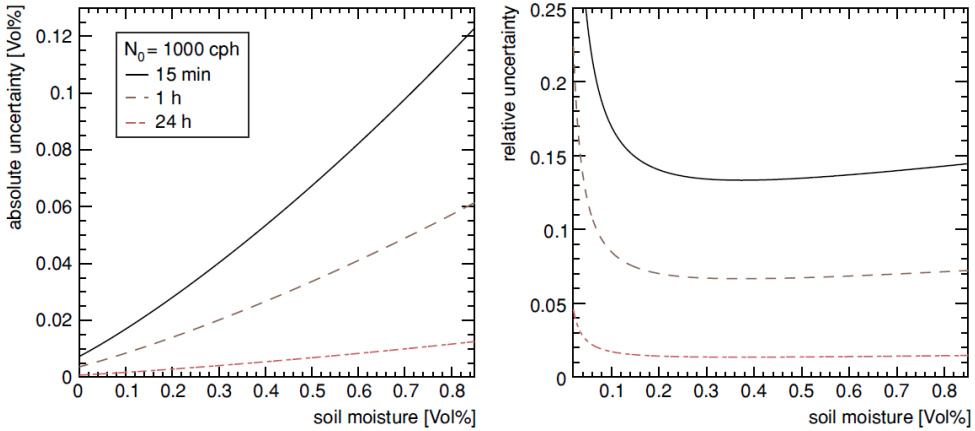
Uncertainties

$$C_I = 1 + \gamma\left(\frac{I_{\text{ref}}}{I} - 1\right) \qquad \gamma = 1 - 0.075\left(R_C - R_C^{\text{ref}}\right)$$

$$C_p = \exp\left(\frac{X - X_{\text{ref}}}{\lambda_{\text{atm}}}\right)$$

$$C_h = 1 + \alpha_{\text{hum}}\left(h_{\text{abs}} - h_{\text{abs}}^{\text{ref}}\right)$$

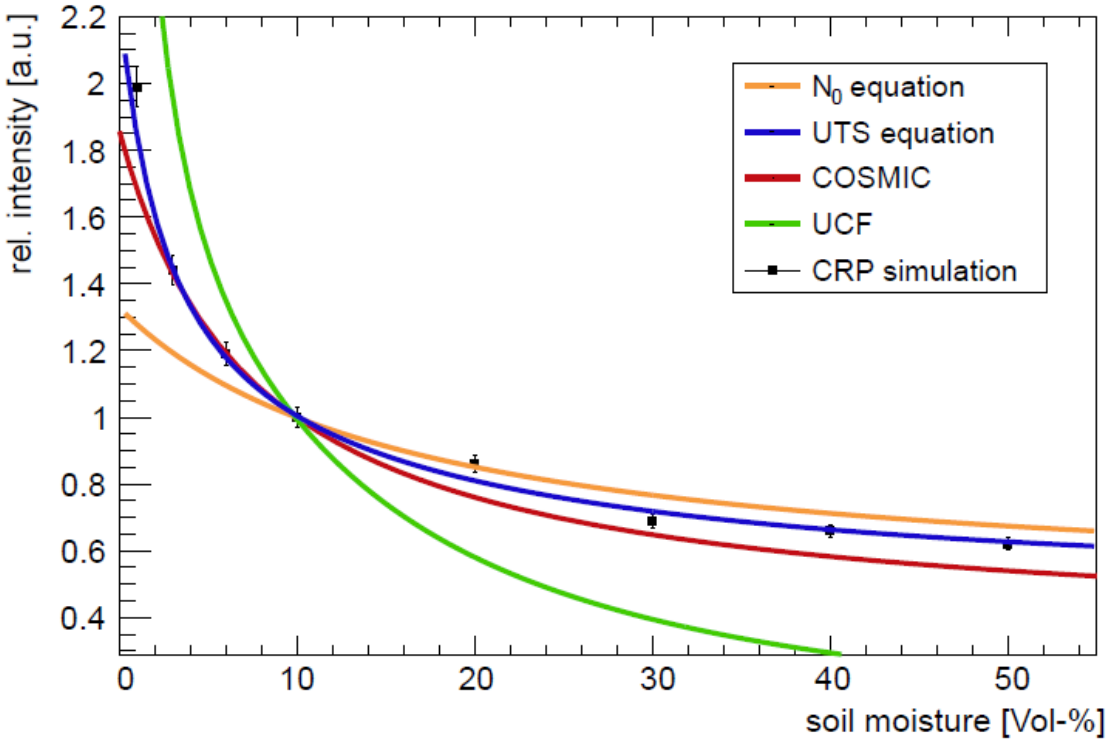
$$N_{\text{corr}} = N_n \cdot C_I \cdot C_p \cdot C_h \cdot C_{\text{veg}}$$

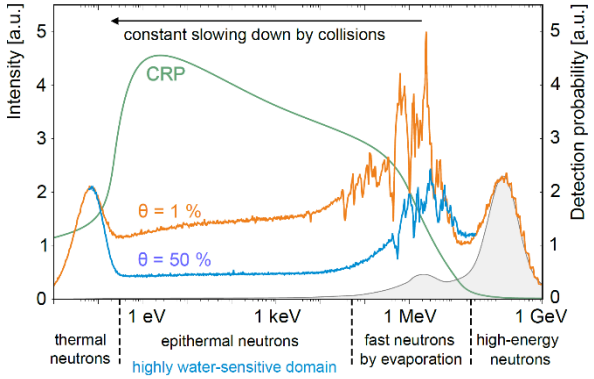


$$C_{\text{veg}} = \frac{1}{1 - 0.009 \cdot \text{AGB}}$$

Soil Moisture Retrieval + Calibration

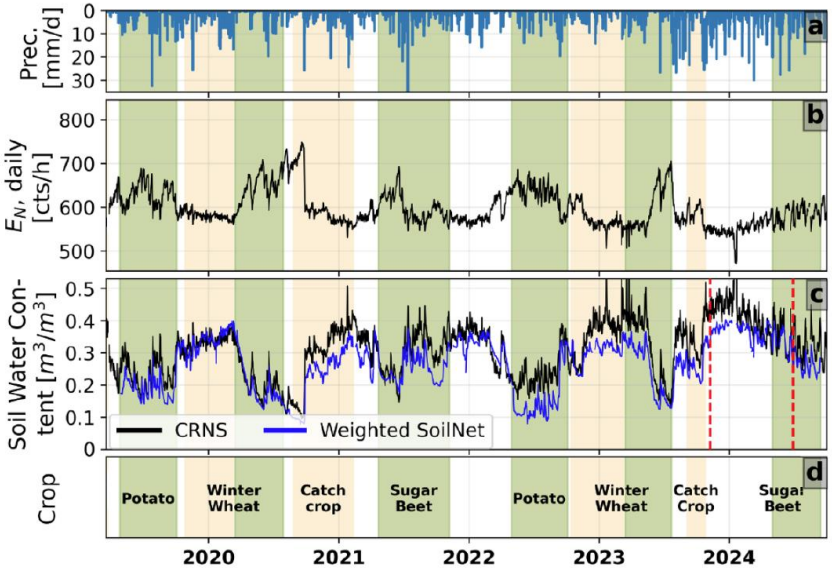
Intensity to soil moisture relation





Signal Generation and Contributors

West Germany



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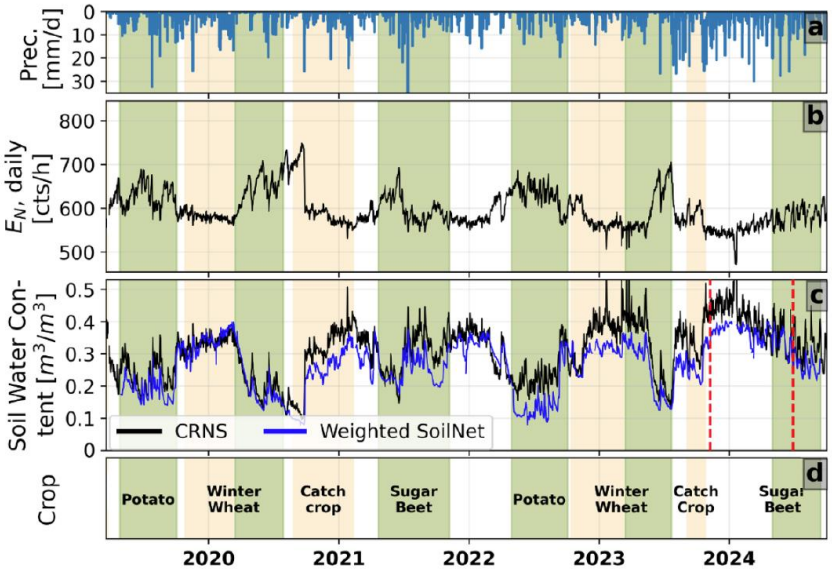
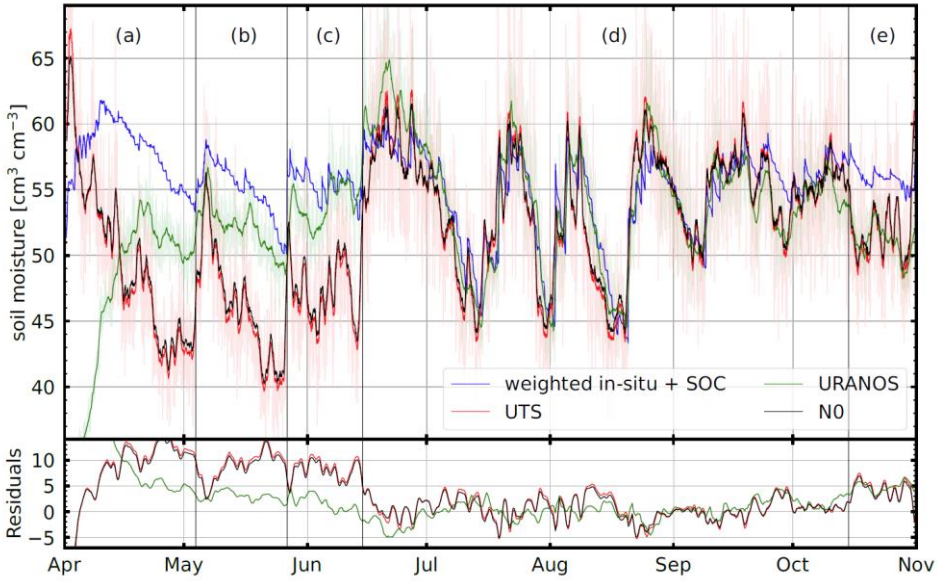
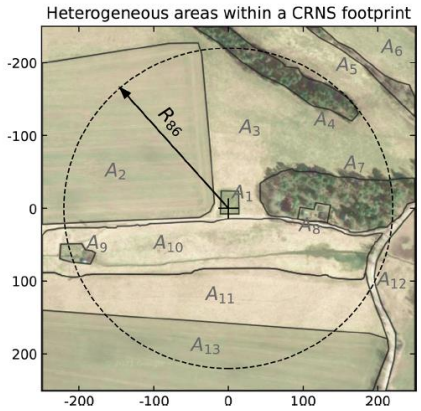
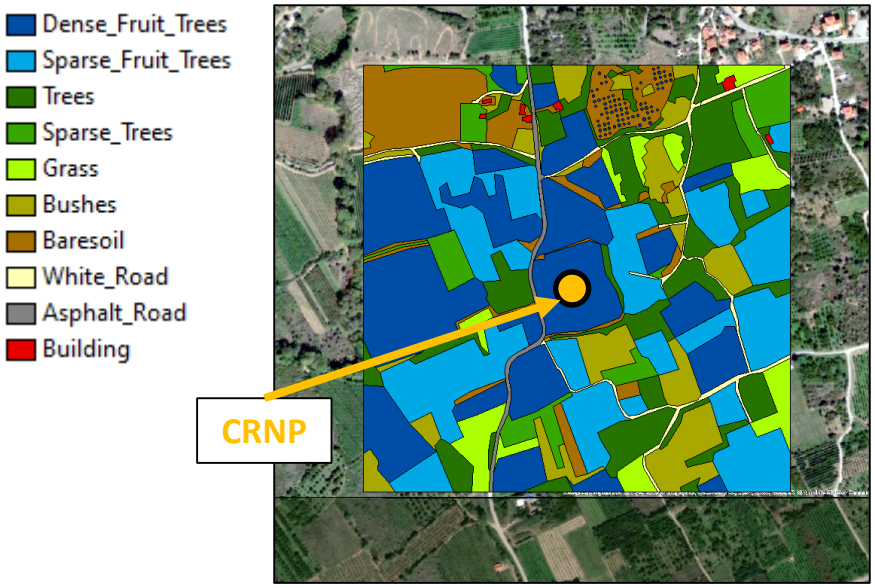


Eastern Tibetan Plateau



Footprint and Inhomogeneities





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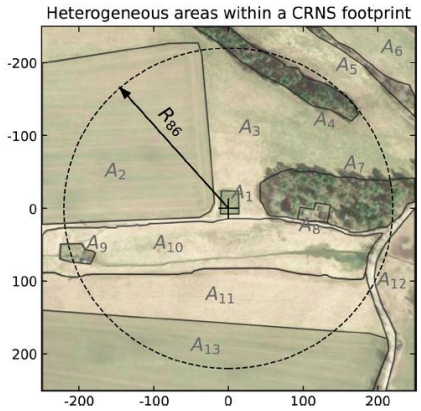
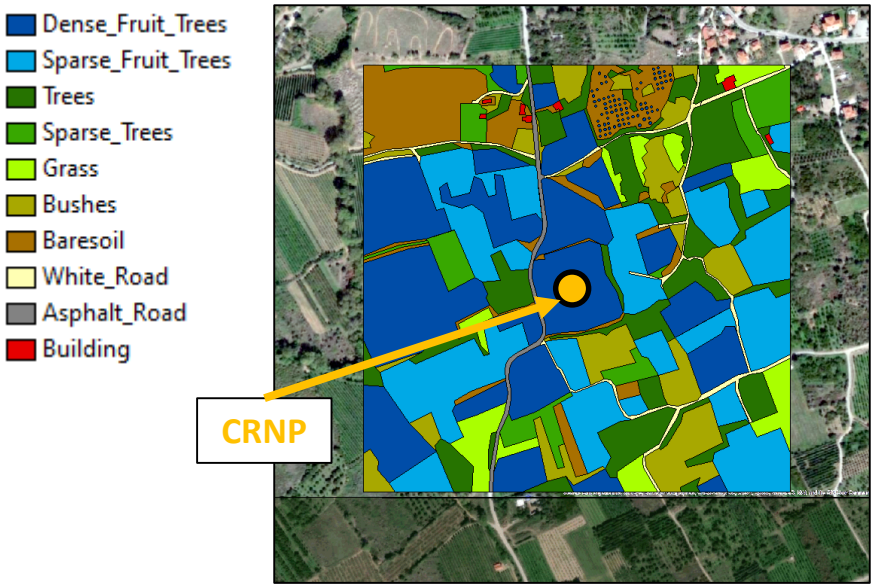
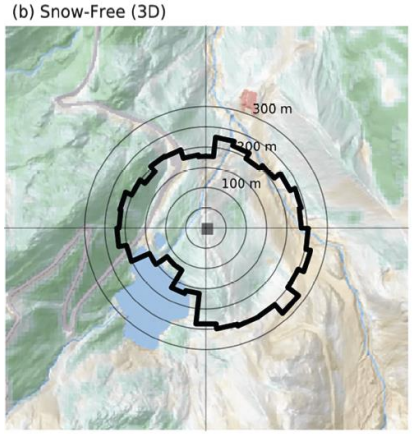
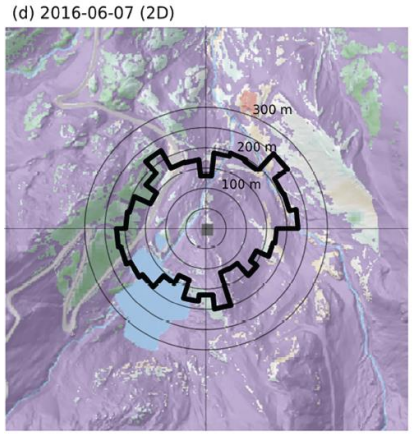
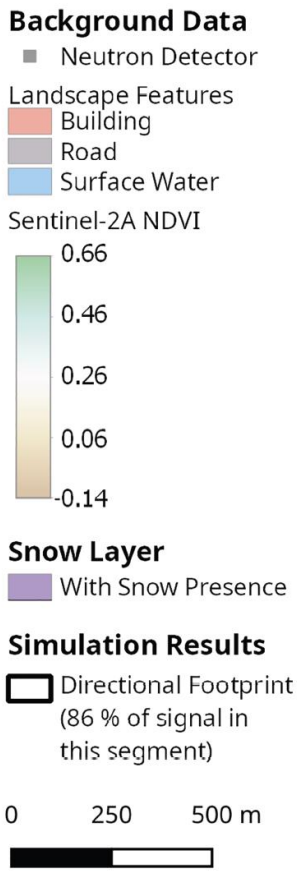






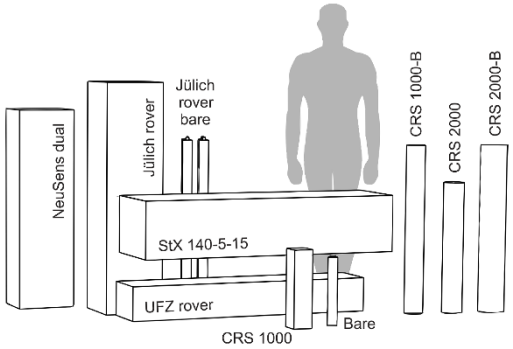




Instrument Standardization

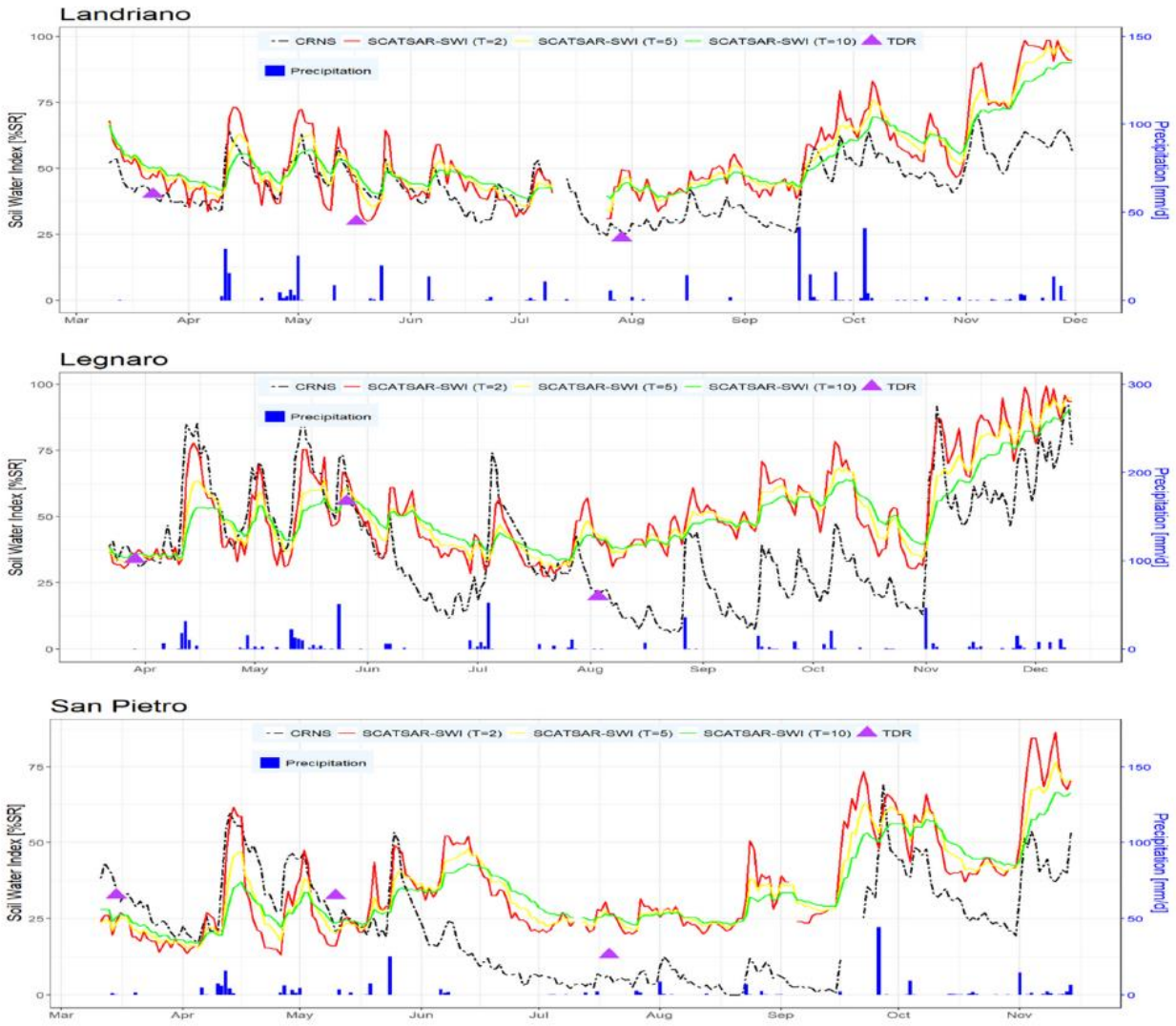
Stationary - small

Stationary - large



Roving

Remote Sensing Comparison



CRNS footprint

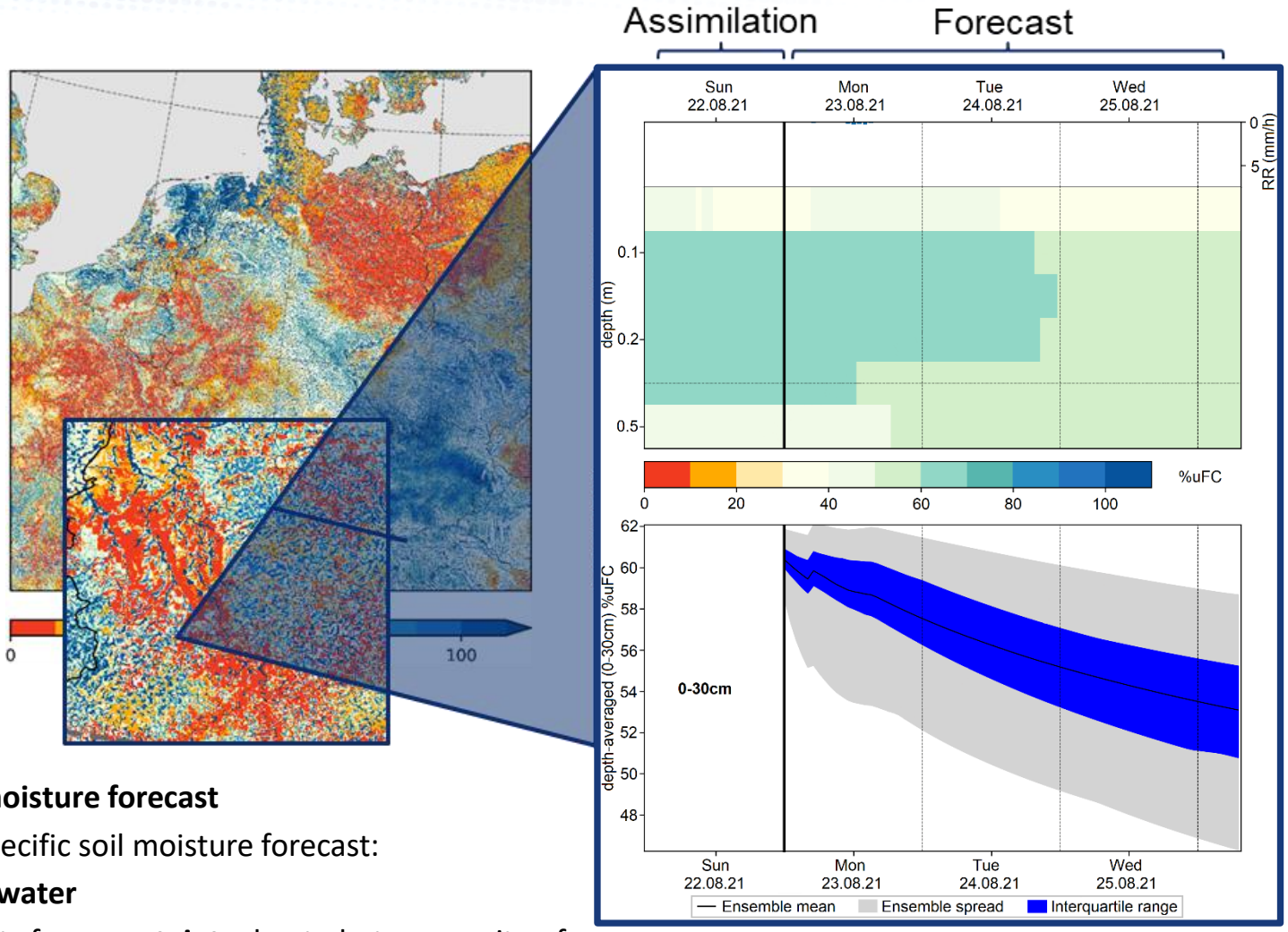
NDVI

- 0 - 0.1
- 0.1 - 0.2
- 0.2 - 0.3
- 0.3 - 0.4
- 0.4 - 0.5
- 0.5 - 1

S. Emamalizadeh et al. (2024): „Comparison of SoilWater Content from SCATSAR-SWI and Cosmic Ray Neutron Sensing at Four Agricultural Sites in Northern Italy: Insights from Spatial Variability and Representativeness“

Hydrological Model Integration

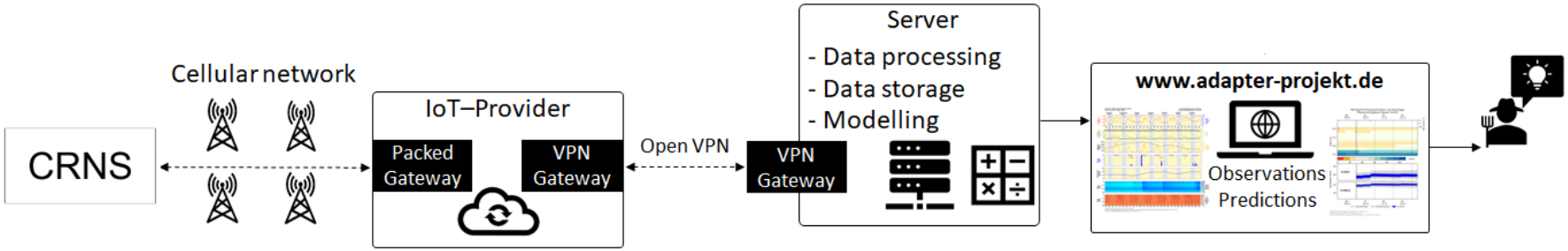
Model: ParFlow/CLM
Forcing: ECMWF HRES

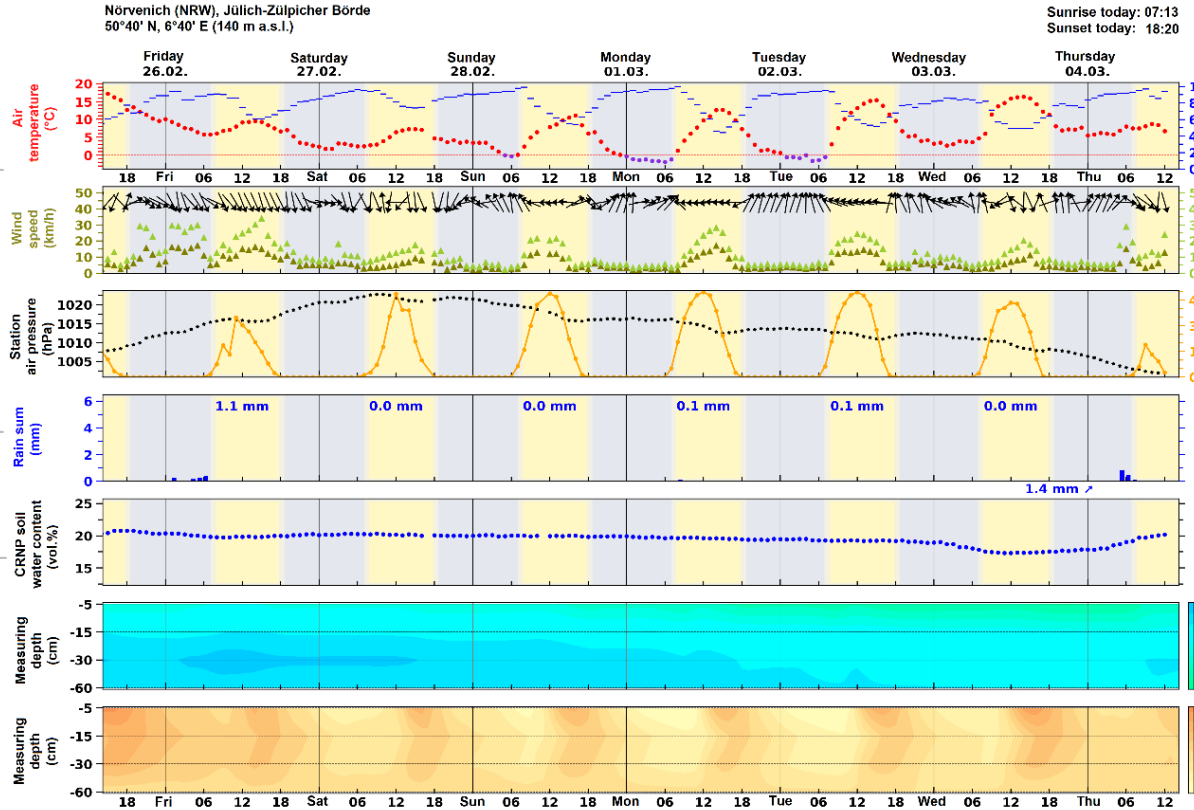


High-resolution soil moisture forecast

- Prototype: site specific soil moisture forecast:
  e.g., **plant available water**
- Ensemble accounts for **uncertainty** due to heterogeneity of soil hydraulic properties

Vertical Integration in Farming





air temperature

wind speed

air pressure

precipitation rate

CRNP
soil water content

relative humidity

wind gust

solar radiation

SoilNet
soil water content

soil temperature

Soil moisture measurements based on Cosmic-Ray Neutron Sensing – current status and open questions

CRNS as an emerging technology platform

Markus Köhli
Physikalisches Institut
Heidelberg University
Germany

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- Independent modeling + simulation
  converging to experimental results

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- Solutions for detection systems
  - Independent, non-invasive sensor operation and low maintenance

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- Independent modeling + simulation
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- Solutions for detection systems
  - Independent, non-invasive sensor operation and low maintenance
- Comprehensive understanding,
  - but smaller open questions remain

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CRNS as an emerging technology platform

- Independent modeling + simulation
  converging to experimental results
- Solutions for detection systems
  - Independent, non-invasive sensor operation and low maintenance
- Comprehensive understanding,
  - but smaller open questions remain
- CRNS is on the way to become
  the most precise method of measuring soil moisture

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Heidelberg University
Germany